PATENT SPECIFICATION 1,012,283

DRAWINGS ATTACHED.

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COMPLETE SPECIFICATION.

Optical Method and Apparatus for the Measurement of Minute Displacements.

We, ETAT FRANCAIS represented by the MINISTRE DES TRAVAUX PUBLICS (LABORATOIRE CENTRAL DES PONTS ET CHAUSSEES) of Paris (Seine) France, 58 Boulevard
5 Lefebvre, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:
10 This invention relates to an optical method, based on the so-called mechanical interference fringe effect, or "moiré" effect, for the measurement of extremely small displacements, and to apparatus operated in
15 accordance with the method and useful as strain-gauges.

For the measurement of minute displacements, such as are encountered in the gauging of deformations sustained by structural
20 elements in concrete and metallic structures, various techniques have been developed, most of which have been based on the variation in optical or electrical characteristics in a member subjected to strain or
25 deformation. These techniques, while possessing a high sensitivity and being satisfactory in the analysis of dynamic phenomena, i.e. transient deformations of relatively high time rate, present difficulties when
30 applied to the measurement of long-term deformations varying slowly with time, because of the inevitable zero-shift or drift which characterizes instruments based on the principles mentioned above.
35 It is a broad object of this invention to provide a new method and apparatus for the measurement of minute displacements, especially useful in connection with strain-gauging, which will be inherently free from
40 such drift, will be highly sensitive yet simple and rugged.

ical interference fringe effect, or moiré effect, which will now be briefly described. Consider two optical gratings each formed by a series of fine straight, parallel lines of small 45 uniform spacing or pitch, engraved or otherwise provided on respective thin plates of rigid transparent material. When two identi- 50 cal such grating patterns are superimposed, with the directions of the lines therein forming a small angle α as between the two gratings, then a pattern of dark fringe bands becomes visible; the fringe bands extending 55 in parallel directions normal to the bisector of the angle α between the two gratings, and being uniformly spaced in the direction of said bisector by a pitch of considerably greater length than the pitch of either of the 60 grating patterns. These dark fringe bands are actually the loci of the points at which the lines of one grating lie exactly intermediate two adjacent lines of the other grating. As will be shown more fully hereinafter, 65 measuring the variation of the inter-fringe spacing resulting from a very small variation in the angle α or alternatively measuring the fringe shift resulting from a small parallel translational displacement between 70 the two patterns, provide extremely sensitive methods of measuring rotational and translational displacements, as the case may be, occurring between the gratings. Owing to the inherently geometric character of the 75 method, practically no zero shift or drift can occur and the fidelity, in addition to the sensitivity, of the resulting measurements is extremely high.

The invention will now be described 80 for purposes of illustration but not of limitation with reference to the accom-

panying diagrammatic drawings, wherein:

Fig. 1 is a simplified and partly schematic front view of a device according to the invention, usable as a strain gauge, and in which the relative displacement between two reference points of a measuring base is converted into relative rotation between the two optical gratings;

Fig. 2 is a similar view of device according to another embodiment of the invention wherein the relative displacement between the two reference points is converted into parallel displacement between the two gratings.

The two embodiments of the invention illustrated are largely identical and most of the description to follow applies to both figures. The difference between the two embodiments will be pointed out at the appropriate place.

In each case the device comprises a pair of straight rigid plates, bars, or strips 1 and 2 disposed parallel with their respective ends interconnected by resiliently flexible spring strips 3 and 4. The bar 1 has a knife-edge member 5 suitably secured to its inner side near one end of the device and projecting towards the other bar 2, and similarly the bar 2 has a knife-edge member 8 secured to it in a corresponding position near the other end of the device and projecting towards the bar 1. It should be understood that the two knife-edge members 5 and 8 are adapted to be rigidly secured at their tips to two spaced reference points of a structure, or structural member, the relative displacement between which points, due e.g. to a deformation of the structural member, is to be measured by means of the device. In other words in the initial or neutral condition of the device, as will be presently clear, the tips of the knife edges 5 and 8 define the measuring base.

The device further includes a pair of T-shaped linkage levers 11 and 13. The crossbar of the T-lever, designated 11b and 13b respectively, extends normally to both bars 1 and 2 and projects freely through holes 1a—1b, and 2a—2b, formed respectively in said bars at suitable positions as shown. The longitudinal member 11a or 13a of each T-lever extends inwardly in between the bars 1 and 2 and has secured to its end a grating member 12 and 14 respectively. The two gratings members 12 and 14, which are thin rigid strips of suitable transparent material, are supported in parallel closely-spaced planes so as to be substantially superposed.

Two further knife-edge members 6 and 7, secured to the inner side of the bar 1, are bent outwards so that their tips are pivotally fulcrummed against the inner sides of the T crossbars 11b and 13b, and two further knife-edge members 9 and 10 similarly secured to bar 2, are bent so that their tips are pivotally fulcrummed against the inner sides of the said crossbars. Tension springs 15 and 16 having their opposite ends attached to the outer ends of the crossbars 11b and 13b draw the T-levers towards each other into engagement with the tips of the knife-edge members 6—9 at one end, and 7—10 at the other.

At this point intervenes the difference between the two embodiments. Whereas in the embodiment of Fig. 2 the knife-edges 6 and 7 secured to bar 1 both engage the T-crossbars to one side of the longitudinal center line of the device and the knife-edges 9 and 10 secured to bar 2 both engage the crossbars on the other side of said center line, in the Fig. 1 embodiment of the two cross bars 7 and 10 at one end of the device (right-hand end as shown) are crossed over, as clearly shown in the schematic illustration. so that at the said (right-hand) end of the device the knife-edge 7 extending from bar 1 engages the crossbar of the related T-lever 13 on the other side of the longitudinal midline of the device from the side where the knife-edge 6 extending from bar 1 engages the crossbar of its related T-lever 11; and the same relationship applies for the knife-edges 9 and 10 extending from the other bar 2. The significance of this relationship will appear presently.

It will be understood that each of the grating members 12 and 14 is provided with a grating array of fine parallel uniformly spaced lines engraved thereon, extending generally longitudinally of the device, i.e. horizontally of the drawing. These arrays have not been shown. But the dark fringe bands, that appear whenever there is even an extremely small angling between the two grating members, i.e. whenever the two sets of lines in the respective arrays are not exactly parallel, have been summarily indicated as wavy lines extending generally normal to the general direction of the pattern lines; to be precise normal to the bisector of the angle formed between the two sets of lines.

In the operation of the device of Fig. 1, it will be easily seen that any variation in the distance between the ends points of the measuring base, i.e. the tips of knife-edges 5 and 8, will result in a rotation of the T-levers 11 and 13 therewith the grating plates 12 and 14 in opposite directions. For example should the end points of the measuring base, i.e. the tips of knife-edges 5 and 8, move away from each other, then the bar 1 can be visualized as moving leftward, bar 2 rightward. This relative movement of the bars causes counterclockwise rotation of T-lever 11 and grating 12, and, owing to the cross-over between knife-edges 7 and 10, clockwise rotation of T-levers 13 and grating 14. Thus the angle α between the two

parallel arrays on the respective gratings is varied. The same of course is true in the case of a contraction, rather than an elongation, of the measuring base.

In the device of Fig. 2, on the other hand, a similar reasoning shows that any change in the length of the measuring base causes rotation of both T-levers and both gratings 12 and 14 in the same sense, i.e. both counterclockwise in the case of an elongation, both clockwise in the case of a contraction, in the specific example shown. With both grating patterns being rotated in opposite directions by equal angles, it will be clear that the net effect is a parallel translational relative displacement between the two parallel arrays. Any angle α initially present between the directions of the respective arrays will remain unaltered, but a bodily shift of the fringe lines will be observed.

The following summary mathematical analysis will assist in understanding the operation of the invention.

Let e be the common pitch of grating arrays in either device, i.e. the uniform mean transverse spacing between adjacent lines of the arrays; than the inter-fringe spacing i, that is the longitudinal spacing between the fringe bands that are observed when the two patterns are angled by a small angle α, is given by the formula

$$i = \frac{e}{2 \sin \frac{\alpha}{2}} \qquad (1)$$

or, since the angle α is small,

$$i = e/\alpha \text{ (approx.)}. \qquad (2)$$

Assuming first that the angle α between the two patterns is varied by a small quantity $\Delta\alpha$, as is the case during a measurement performed with the device of Fig. 1, then differentiation of equation (2) shows that the interfringe spacing i sustains a corresponding variation Δi given by the formula

$$\Delta i = -\frac{e}{\alpha^2} \Delta\alpha = \frac{i^2}{e} \Delta\alpha \qquad (3)$$

so that provided the grating pitch e is small enough, it will be seen that an extremely small variation $\Delta\alpha$ in angle can be detected as a relatively large variation Δi in the interfringe spacing i.

If on the other hand the angle α is assumed to remain unaltered, but the two grating patterns are displaced by parallel translation with respect to each other in a direction substantially normal to the bisector

of the angle α, as is the case in the operation of the embodiment of Fig. 2, then the interfringe value i remains unchanged. The fringes are bodily shifted in a direction parallel to the bisector of the angle α. It can be shown that the amount of shift sustained by the set of fringes attains a value equal to one interfringe spacing i, when the amount of relative displacement Δy between the two grating patterns, as measured in a direction normal to that of said bisector, becomes equal to

$$\Delta y = \frac{e}{\cos \frac{\alpha}{2}} \qquad (4)$$

or, since α is small,

$$\Delta y = e \text{ approx.} \qquad (5)$$

Thus, every time the two gratings are shifted relative to one another the approximate amount of one pitch spacing, the fringe bands are seen to shift bodily by the amount of one interfringe spacing. By counting the number of fringe bands that are seen to move past a fixed marker point, such as the intersection of the cross-wires in an optical system, it is thus possible to determine the relative displacement Δy with great accuracy. Specifically, if there are mounted n fringes moving past the optical marker point, plus an excess of $\frac{p}{q}i$ fringes, p/q being an approximately evaluated fractional number, then the displacement Δy sustained between the two gratings can be estimated as

$$\Delta y = (n + \frac{p}{q})e \qquad (6)$$

with considerable precision, the sensitivity or magnitfication factor being in this case also 1/e.

The two knife edge members 5 and 8 are suitably connected to the end points of the measuring base, which may be points of a common structural member whose deformation is to be measured, or points of two structurally connected members whose relative displacement is to be measured as a measure of the deformation of the structure of which they form part. The connections of the knife edges 5 and 8 with said member or members may be effected directly or through any appropriate kinematic transmissions.

Depending on the particular application, the embodiment of Fig. 1 or that of Fig. 2

may be preferred. Each system has its advantages in specific circumstances. Thus, the embodiment of Fig. 1 is especially well-suited in the case of very long-term deformation effects. The measurement involves a comparison between the initial and final values of the interfringe spacing. This comparison can conveniently be effected by means of a telescope mounted on a displaceable carriage provided with micrometric screw adjusting means. Alternatively, photographic camera means may be used to record the initial and final interfringe spacings which can then be measured on the photograph plates. The comparison measurement, however obtained, provided the quantity Δi, the variation in interfringe spacing, from which the corresponding variation $\Delta \alpha$ is derived using equation (3). From the value $\Delta \alpha$ in turn, the linear displacement between the two boundaries of the measuring base can be inferred as by simple multiplication with a factor constituting a constant of the apparatus used.

The second method, embodies in the apparatus of Fig. 2, is advantageous in the evaluation of shorter-term displacements and deformations since all it requires is a simple counting operation, easily performed with accuracty provided the rate of motion of the fringe bands past the marker point and hence the rate of deformation, does not exceed certain upper and lower limits. If however the rate of deformation is so slow that the time required exceeds the capacity of attention of a single observer, or on the other hand is so fast that the moving fringes cannot conveniently be counted visually, than the apparatus of Fig. 2 can still be used, if desired, provided suitable recording means, e.g. motion-picture, or automatic counting means, are associated with the apparatus. In any case the parallel displacement between gratings can be derived through use of the formula (6), and the corresponding displacement or deformation of the measuring base can then be derived, again by multiplication with a constant of the apparatus. The sense of the deformation, i.e. whether it is an elongation or a contraction, is of course determined from the sense of the fringe shift observed.

It will be understood that the illustrations of the apparatus according to the invention as given in Figs. 1 and 2 are highly schematic and simplified, and the practical instruments used would include details of construction not shown, some of which are briefly indicated below.

To reduce to a minimum the influence of temperature variations the bars 1 and 2 are preferably made from material having a very low thermal expansion coefficient, such as the alloy known by the trade name "Fix-invar". For maximum precision in the instrument, each apparatus should preferably be calibred individually to ascertain its particular response to temperature, and a table correcting factors with temperaurte drawn up.

Depending on the particular use to which the apparatus is put, the bearings of the knife-edges 5 and 8 on the end points of the measuring base may be effected in any suitable manner. Thus where the device is used as a strain gauge for indicating the behaviour of concrete structures under stress, the knife edges 5 and 8 may be made to bear against respective metallic platelets firmly secured through any suitable means to the rough surface of the concrete.

While the drawings show the grating members 12 and 14 as being directly secured to the ends of the T-levers 11 and 13, the connection for at least one of said members preferably includes according to the invention means, including a micrometric screw device, for adjusting the relative inclination between the two grating members 12 and 14 in the initial or neutral condition of the apparatus. Adjusting means are also preferably provided for accurately setting the two members in strictly parallel planes.

As earlier mentioned, there is associated with the apparatus suitable visual observation and/or recording or counting means, for measuring the variation in interfringe distance, or the bodily fringe shift, as the case may be. Such means may include a telescope, a still or motion picture camera, with suitable optical system, and/or a counter.

As an indication of the degree of sensitivity attainable with the apparatus of the invention, it is pointed out that in the case of the apparatus of the type shown in Fig. 1, with the use of gratings of good, standard manufacture having a pitch of about 0.05 mm, the interfringe spacing i can be measured over a range of about from 1 to 20 mm with a degree of sensitivity of $1/100$, making possible an estimation of angular variations $\Delta \alpha$ to within 20 seconds. The over-all measuring accuracy can be greatly increased if the interfringe spacing is measured over a number of consecutive fringe bands rather than between only two. In fact measuring the total interfringe variation $n\Delta i$ over a consecutive array of $(n+1)$ fringe bands will multiply the sensitivity, i.e. divide the error, on the measurement of an angular variation $\Delta \alpha$ by the factor n. Thus, if $i=5$ mm and $n=10$, the measurement being effected over an array of eleven fringes, i.e. an over-all interfringe length of 50 mm, will reduce the error in the $\Delta \alpha$ measurement to as little as 2 seconds. The accuracy can of course be further increased as desired in the way just indicated.

In the case of systems of the type shown

in Fig. 2, under similar conditions the error in displacement measurement is of the order of 0.5 micron. Using two similar gratings of 0.05 mm pitch, it is possible to measure a relative rotation to within 2 seconds of angle, or a relative parallel displacement, normally to the fringes, to within 0.5 micron.

Various other alterations and adjunctions can be made in and to the apparatus described without exceeding the scope of the invention as defined by the appended claims. The apparatus is characterized by its remarkably high sensitivity, which remains constant throughout the range of measurement of the instrument, and the absence of zero shift or drift with time.

WHAT WE CLAIM IS:—

1. Apparaus for measuring minute changes in the distance between two spaced reference points of a measuring base, which may be points of a common structure or two independent structures, which comprises two generally transparent optical grating members respectively bearing similar arrays of fine parallel spaced lines thereon; means for supporting both members in substantially superposed relation with the line array on one grating member extending at a small angle to the line array on the other grating member so as to create an apparent pattern of fringe bands normal to the bisector of said angle and spaced along said bisector an interfringe spacing many times larger than the spacing between the lines of each array; and linkage means connecting said members to the respective reference points of said structure or structures whereby a change in the distance between said reference points will result in a corresponding relative displacement between said members and a corresponding displacement of said fringe pattern to provide an amplified measure of said change in distance.

2. Apparatus according to claim 1, wherein said linkage means are arranged to convert changes in the distance between said reference points into a relative rotation between said members, whereby the change in interfringe spacing will constitute a magnitude measure of said change in distance.

3. Apparatus according to claim 1, wherein said linkage means are arranged to convert changes in the distance between said reference points into a parallel relative displacement between said members, whereby the bodily shift of said fringe pattern will constitute a magnified measure of said change in distance.

4. Apparatus according to any of claims 1—3, wherein said supporting and linkage means comprise a pair of generally parallel spaced support elements connected for limited resilient relative displacement there-

between, means fixedly securing a point adjacent one end of one of said elements and a point adjacent the remote end of the other of said elements to said reference points of the structure respectively, whereby a change in the distance between said points will cause a relative displacement between said elements, and a pair of linkage members each supporting a respectively related one of said grating members and each having spaced points thereof pivotally connected to both of said supporting elements adjacent a respectively related one of said ends of the elements, whereby said relative displacement between the elements will cause a pivotal displacement of each of said grating members.

5. Apparatus according to claim 4 as appended to claim 2, wherein the pivotal connections of each of said linkage members with both said supporting elements at the respectively related ends thereof are such that the relative displacement between said elements causes the grating members to be pivotally displaced in reverse, i.e. clockwise and counterclockwise, directions.

6. Apparatus according to claim 4 as appended to claim 3, wherein the pivotal connections of each of said linkage members with both said supporting elements at the respectively related ends thereof are such that the relative displacement between said elements causes both grating members to be pivotally displaced in a common, i.e. clockwise or counterclockwise direction.

7. Apparatus according to any of claims 4—6 wherein said supporting elements are connected for limited resilient relative displacement therebetween by means of flexible resilient spring strips interconnecting adjacent ends of said elements.

8. Apparatus according to any of claims 4—7, wherein said linkage members are T-shaped members each having an intermediate leg to which a respectively related grating member is secured and a cross-leg pivotally engaged on opposite sides from said intermediate leg by knife-edge members projecting from said elements, and spring means bias said cross-legs of the T-shaped members into engagement with said knife-edge members.

9. Apparatus according to claim 8, wherein the cross-legs of the T-shaped members extend laterally beyond said supporting elements and said spring means are tension springs interconnecting corresponding ends of the cross-legs of both the T-shaped members.

10. Apparatus according to claim 9 as appended to claim 5, wherein the two knife-edge members extending from each of said supporting elements are arranged pivotally to engage the cross-legs of the respectively related T-shaped members on opposite sides

of the intermediate legs of said last members.

11. Apparatus according to claim 9 as appended to claim 6, wherein the two knife-edge members extending from each of said supporting elements are arranged pivotally to engage the cross-legs of the respectively related T-shaped members on the same sides of the intermediate legs of said last members.

12. Apparatus according to any of claims 4—11, wherein at least one of the gating members is supported from the related linkage member by way of micrometer means for adjusting the relative angle between the grating members.

13. Apparatus according to any of claims 4—12, wherein the means for fixedly securing a point of each supporting element to a related one of said reference points comprises a knife-edge member projecting from said element towards the other element.

14. Apparatus for measuring minute changes in distance between two spaced reference points of a structure, substantially as described with reference to, and as illustrated in Fig. 1 or Fig. 2 of the accompanying drawings.

15. A method of measuring minute changes in distance between two reference points of a structure using apparatus according to claim 2, claim 5, claim 10, or any of the claims 4, 12 or 13 as appended to any one of said claims 2, 5 and 10, which comprises measuring the inter-fringe spacing before and after said change in distance and determining the difference between said measurements.

16. A method of measuring minute changes in distance using apparatus according to claim 3, claim 6, claim 11, or any of claims 4, 12 or 13 as appended to any one of claims 3, 6 and 11, which comprises counting the number of fringe bands apparently moving past a fixed marker point during said change in distance.

17. A method of measuring minute changes in distance substantially as described in the specification with reference to Fig. 1 or Fig. 2 of the accompanying drawings.

BARON & WARREN,

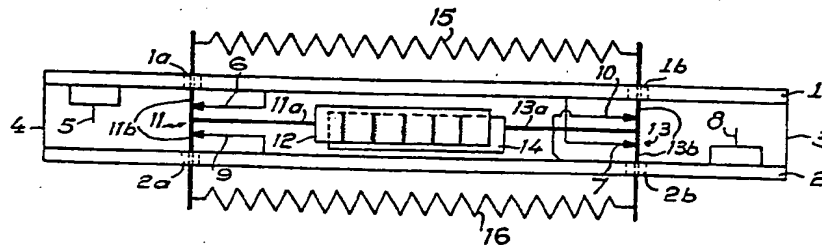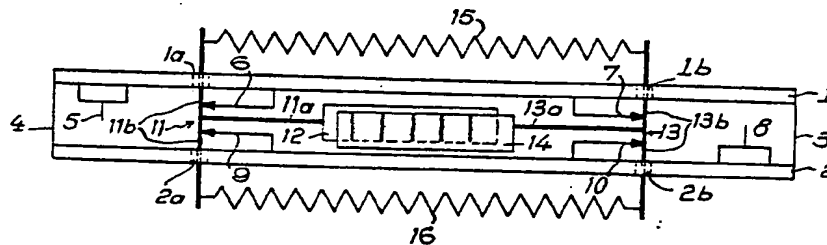16, Kensington Square,

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Fig. 1

Fig. 2